Present status of the Liquid Breeder Validation Module for IFMIF

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HIGHLIGHTS

- The LBVM will be used to perform irradiation experiments on functional materials for fusion reactors.
- It houses 16 experimental rigs, each one containing a EUROFER capsule partially filled with lithium lead, at 300–550 °C.
- A helium purge gas will sweep the tritium permeated through the capsule walls to a tritium measuring station.
- A helium cooling system will keep tritium diffusion within safe margins and guarantee its mechanical integrity.
- Thermal hydraulic and mechanical calculations, the module instrumentation and aspects as safety or RAMI are presented.

ABSTRACT

One of the objectives of IFMIF (International Fusion Materials Irradiation Facility), as stated in its specifications, is the validation of breeder blanket concepts for DEMO design. The so-called Liquid Breeder Validation Module (LBVM) will be used in IFMIF to perform experiments under irradiation on functional materials related to liquid breeder concepts for future fusion reactors. This module, not considered in previous IFMIF design phases, is currently under design by CIEMAT in the framework of the IFMIF/EVEDA project.

In this paper, the present status of the design of the LBVM is presented.

Keywords:
IFMIF
Test Facilities
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1. Introduction

The LBVM is one of the medium flux test modules of IFMIF [1]. The objective of this module is to deal, in a versatile set up, with some of the R&D needs of the Liquid Breeder Blankets that require irradiation experiments under a relevant neutron environment and the expected temperature operational conditions in DEMO. Then, the module is being designed to achieve the required range of temperatures and other operational conditions on each experimental capsule. In addition, the LBVM should assure some flexibility to accommodate possible changes in the irradiation test matrix due to the evolution on the R&D necessities. The LBVM will be focused, as first approach, on experiments related to the HCLL DEMO blanket concept, which is based on LiPb as breeder and EUROFER as structural material at temperatures 300–550 °C. However, the possibility to tackle experiments related to other liquid breeder concepts could be assessed in the future.

2. Experimental capability

Some research areas have been proposed to be feasibly investigated in the LBVM of IFMIF. These are:

- The PbLi behavior under irradiation to test different alloy production technologies [2].
- The corrosion of EUROFER and functional materials in stagnant Pb–15.7Li under irradiation [2].
- The behavior under irradiation of anti-corrosion/anti-permeation barriers in contact with stagnant Pb–15.7 Li [2,3].

3. Neutronic relevance of the experiments

The main irradiation parameters (dpa, He/dpa and H/dpa) and also the primary recoil atom (PKA) spectra for iron and ceramic functional materials in the LBVM have been obtained in past design

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Table 1
Neutronic characteristics of the LBVM (for Fe-56) in the most irradiated capsule.

Position in the TC	HFTM–LBVM–others	HFTM–W NSS–LBVM–others
Total n flux (n/cm^2/s)	3.5×10^{14}	1.5×10^{14}
H/dpa (appm/fpy)	45	30
He/dpa (appm/fpy)	14	9
Dpa	13	2
Nuclear heating (W/g)	1	0.3

activities [4,5]. Taking into account the neutronic calculations performed, the medium flux area has been found to be the best position to install the LBVM inside the Test Cell (TC) of IFMIF, behind the High Flux Test Module (HFTM). In that position, the LBVM will achieve significant amount of dpa's, with values that fit the ones expected in the DEMO HCLL breeder zone. Nevertheless, the gas production ratios (He/dpa, H/dpa) will be higher than the obtained in DEMO because of the relatively fast neutron spectrum of the IFMIF medium flux area (gas production is a threshold reaction). In order to reduce the gas production ratios to the fusion reactor values, a Neutron Spectral Shifter (NSS) has been proposed to be installed in front of the LBVM to shift the spectrum to lower energies. This NSS has been designed based on tungsten plates of 6–7 mm thickness and it will be used in case of experimental necessity. In this case, lower dpa production is expected. In order to increase the tritium production toward DEMO values, other materials as $ZrH_{1.65}$ could also be used for this particular necessity.

In Table 1 we can see the main neutronic characteristics of the LBVM.

The tritium generation rate in the LiPb content of the capsules will vary depending on the position of the LBVM and the NSS material. Values between 4×10^{17} at/m^3 s (without NSS) and 2×10^{18} at/m^3 s ($ZrH_{1.65}$ NSS) are expected in the most irradiated capsule.

4. Description of the LBVM

The LBVM will be a SS316LN structure containing experimental rigs and capsules. The present configuration, with main components, is shown in Fig. 1.

The principle of operation of the module and the main parameters of the cooling and purge circuits are shown in Fig. 2.

In order to perform the experiments mentioned above, the LBVM will include 16 experimental capsules distributed in two rows containing functional materials to be irradiated and the associated instrumentation (Section 4). The capsules, EUROFER cylinders 80 mm high, 22 mm of external diameter and 1 mm thick walls, will be filled with LiPb up to 50 mm (theoretical height of the neutron footprint). The rest of the volume up to its total height will act as a plenum for allocating the transmutation gases generated during irradiation. Each capsule will be equipped with an electrical heater (from 0 to 250–300 W) to compensate the nuclear heating and achieve the required experimental temperature. This heater will be encircled by an isolation plug made of MACOR in order to isolate the capsule from the irradiation rig described below:

Each capsule will be installed inside an also cylindrical rig (SS316LN) that, on one hand, will support and position the capsule assuring and isolation gap between the rig walls and the capsule. On the other hand, each rig will be connected with the purge gas system that will provide clean helium and will transport the helium plus permeated tritium to the Tritium Measurement Station situated out of the TC. The purge helium will enter from the bottom of the rig, surround the capsule and sweep the tritium permeated throughout the capsule walls. The isolation gap (about 2 mm) will allow a high temperature in the capsules although slightly lower than required by the experiment. The adjustment will be done by the electrical heaters to compensate the real nuclear heating under irradiation. The rig will operate at 50–150 °C as maximum to minimize the tritium permeation throughout its walls.

Each of these rigs will be enclosed by a SS316LN container that will assure the needed cooling around them with a channel 1 mm thick and Reynolds number of 8800. In the upper part of the container, three lip sealed lids will be allocated. The rigs will be installed from the top of the module during the manufacturing and then, each purge pipe will be welded to the central lid. The instrumentation cables will go through the other two lids from the interior of the module to their respective connections in the Test Cell.

This container will be attached to a Test Module Interface Head (TMIH) that will support the module in the TC structure and will

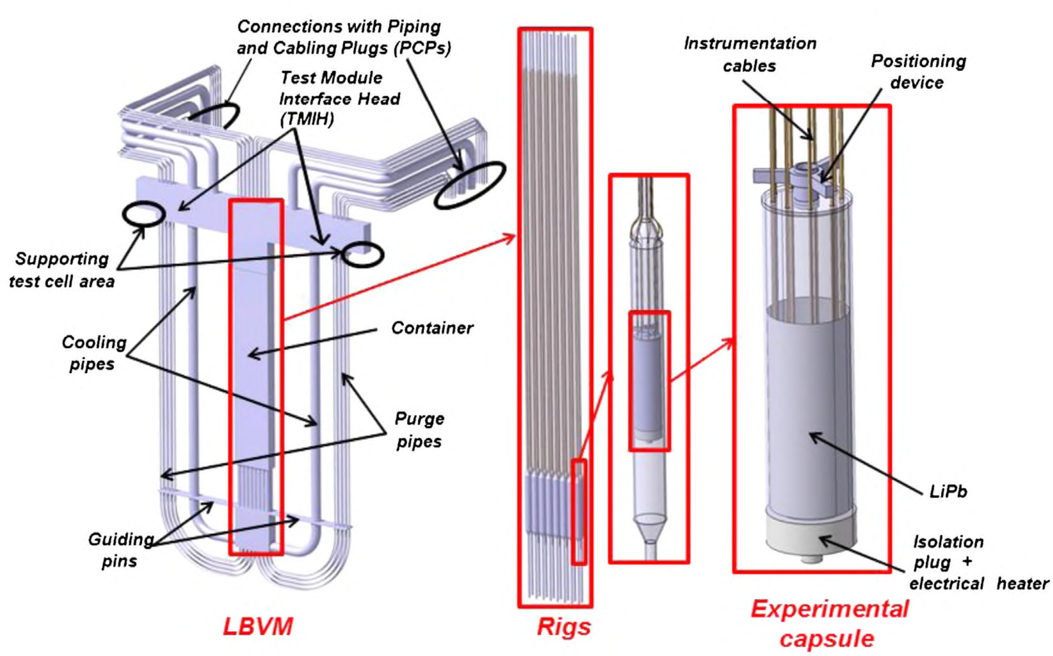

Fig. 1. Present configuration of the LBVM.

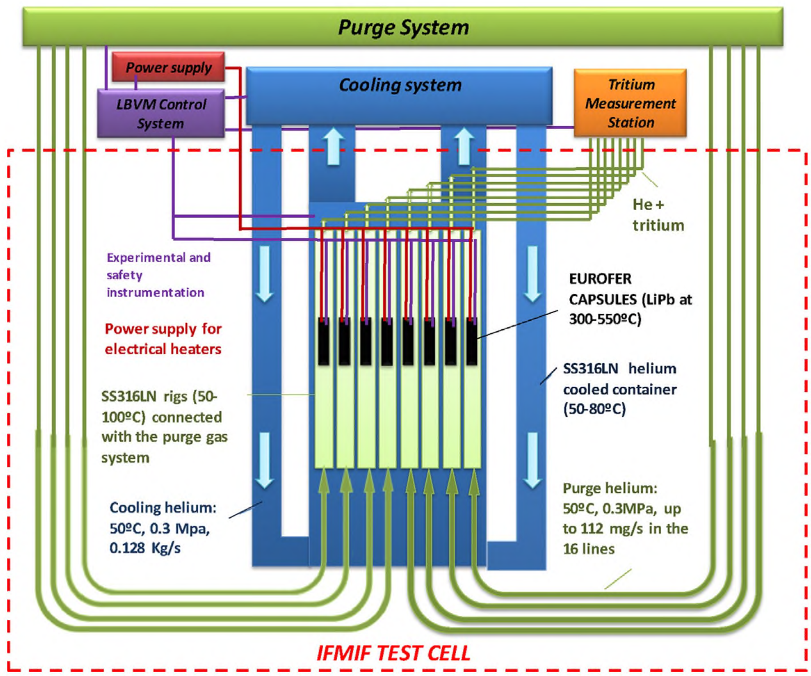

Fig. 2. Scheme of the operation of the LBVM.

serve also as interface for the inlet pipes (purge and cooling) and the instrumentation that will be allocated in the external walls of the container.

5. Instrumentation

The foreseen instrumentation in the LBVM can be divided in two main groups: experimental and safety instrumentation.

The experimental instrumentation includes those sensors directly involved in the correct performance and diagnosis of the experiments [2]:

- Thermocouples: K type, to measure the temperature of the LiPb inside the capsules, since most of experiments need an on-line control of the temperature.
- Ionization chambers: for controlling on-line the gamma fluence rate.
- Fission chambers: to measure on-line the neutron fluence rate with a fast response time.
- Gamma thermometers: to measure the nuclear heating in different positions of the module.
- Activation foils: to supply information after the irradiation about the neutron spectrum.
- Self-powered neutron detector: to measure on-line the thermal component of the neutron flux. Such a measurement is important to determine the tritium generation in the LiPb.

The safety instrumentation (that would request a beam stop) of the module includes:

- Thermocouples: K type, to measure the temperature of some critical areas of the module.
- Strain gauges: to measure deformations and thermal stress of the container due to abnormal (e.g. lack of cooling) heating conditions.
- Manometers and flowmeters: situated outside the TC in the cooling system.

The on-line measurement of the tritium permeated throughout the LiPb capsules walls will be performed by an ionization chamber installed out of the irradiation area [3], in the Tritium Measuring Station.

6. Studies of performances

In order to guarantee the basic performance of the LBVM to accomplish its experimental objective, a set of preliminary studies has been done.

6.1. Thermal-hydraulic analysis

A 3D modeling of the footprint region has been performed with ANSYS CFX [6]. The turbulence model used for the cooling gas has been the Shear Stress Model and formulation for transitional turbulence (gamma theta model) with mesh refinement of $y+$ of 0.02 near walls and neglecting wall roughness. For the purge gas, a laminar flow has been considered. The results show that the required experimental temperature range can be obtained with the present design (Fig. 3) while maintaining the rig and container at low temperature (minimizing the tritium losses).

The expected cooling pressure drop in the testing area (cooling gaps of 1 mm) is 0.023 MPa while the temperature increase is about 15 °C. The heat transfer coefficient obtained in the testing area is 1200 W/m^2 °C. Velocities up to 3 cm/s are obtained in the center of LiPb and some mm/s near walls by natural convection in the liquid metal, which represents an interesting feature from the experimental point of view.

6.2. Mechanical calculations

To guarantee the structural integrity of the module and evaluate protection of the LBVM against plastic collapse under monotonic loading, a numerical analysis has been performed with ANSYS code [6]. The coolant pressure and thermal loads have been considered. The evaluation has been done by using the design code Structural Design Criteria of ITER for In-vessel Components (SDC-IC) [7]. This

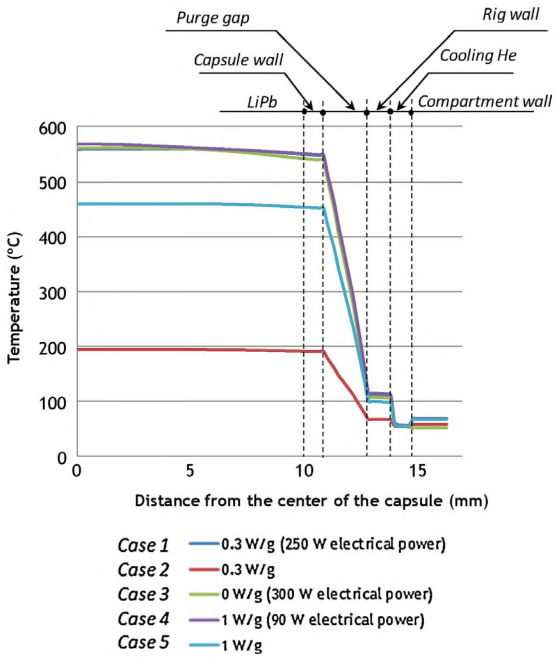

Fig. 3. Temperature in the middle of the footprint.

code has been used instead of RCC-MR or ASME since it includes data for irradiated SS316LN for more than 7 dpa. For the EUROFER capsules data from literature [8] have been used. The stresses obtained in the module and its main components are low enough to accomplish the allowable limits, Fig. 4.

6.3. Tritium transport calculations

TMAP7 [9] has been used to study the T permeation through the capsules walls. Values between 1.8×10^{-4} Ci/m^3 and 4×10^{-2} Ci/m^3 are expected for each purge line, which fall in the measurement range of commercial ionization chambers. The burn-up of the Li-6 content in the LiPb will be negligible for an irradiation campaign of 11 months. On the other hand, the expected T losses to the coolant and TC are negligible. The permeation rates to the coolant will be 5 orders of magnitude lower than that expected toward the purge gas (assuming the rig at 150 °C and the capsule at 550 °C). The permeation rates toward the TC will be 8 orders of magnitude lower than the losses to the coolant (container at 80 °C).

Table 2
Contact dose rates after 1 full power operation year.

LBVM materials (Sv/h)	SS316LN	EUROFER	LiPb
Shutdown	17,000	13,400	13,200
1 day	7000	2300	25
30 days	5100	1900	3
1 year	1000	900	0.9

7. Safety

The safety studies performed include the evaluation of the radiological hazard associated to the activation of materials in the LBVM, the decay heat in the module after irradiation, a safety checklist and FMECA analysis.

The radioactive materials generated in the LBVM during one year of irradiation have been estimated by means of the ACAB code [10] when the LBVM is placed just after HFTM and considering impurities in LiPb. An average of 3.3×10^{12} Bq of T (1.3×10^{16} at/m^3 s) will be generated in the LiPb. However, depending on the configuration used, the amount could be increased as commented in Chapter 2. Also, an average of 1.5×10^{8} Bq of Po-210 (6×10^{11} at/m^3 s) will be produced in the LiPb, that in case of capsule rupture will be present in the purge gas stream. Despite the low production of this volatile material, it has been considered due to its high radiotoxicity. This fact also must be taken into account during the capsule disassembly processes. The obtained contact dose values for the different materials are shown in Table 2. The decay heat in the module will be 140 W just after shutdown.

8. RAMI

A model performed by RISKSPECTRUM [11] has been developed for LBVM to know if the design accomplishes the availability specification for the Test Facilities (96%) and to determine the critical parts

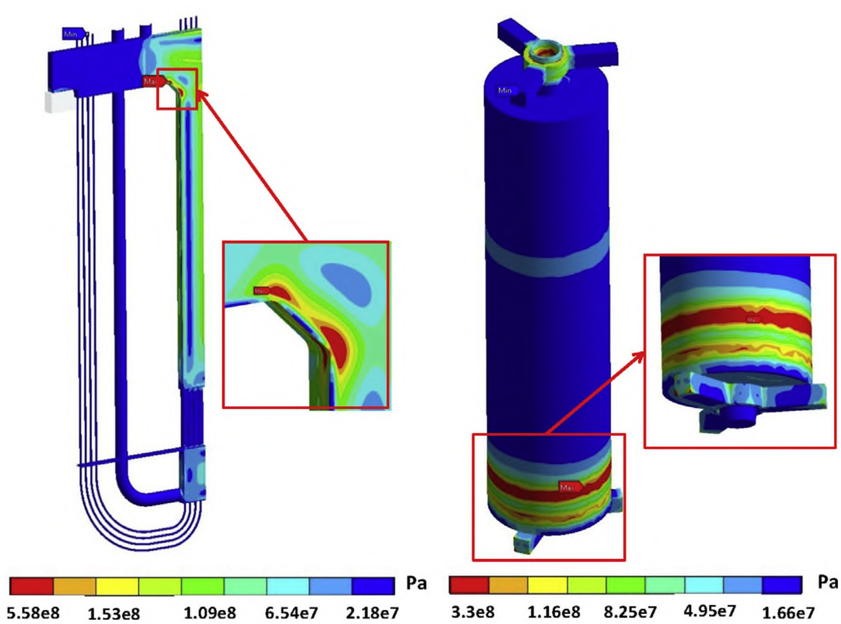

Fig. 4. Stresses obtained in the LBVM.

of the design. The main conclusion indicates that He pipe connections are one of the critical points of the system. Therefore the purge and cooling pipes will be welded to the upper part of the container instead of using bolted connectors. The reliability of the LBVM has increased from 93.9% to 99.3%. Another option for increasing availability is the use of the purge lines as backup cooling system in case of failure. This "degraded" mode of operation is being evaluated.

9. Conclusions

The preliminary design of an IFMIF module (LBVM) focused on irradiation experiments related to the HCLL DEMO blanket concept is being performed by CIEMAT in the framework of the EVEDA project. A set of irradiation experiments at temperatures 300–550 °C, based on EUROFER capsules filled with LiPb has been proposed for the module.

The required instrumentation has been identified, both experimental and safety related. Thermal hydraulic and mechanical calculations performed have demonstrated the feasibility of the design. The radioactive materials, contact dose and decay heat have been calculated for one year full irradiation period. Tritium and Po-210 have been identified as main radiological hazards from the operation of the module. The RAMI analysis of the module has led to some design improvements to increase its availability.

Future work will face transient studies relevant for loss of coolant failures.

Acknowledgments

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